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METHOD AND APPARATUS FOR ELECTROMAGNETIC POSITION AND ORIENTATION TRACKING WITH DISTORTION COMPENSATION EMPLOYING A MODULATED SIGNAL

REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. Patent Application Serial No. 10/428,540, filed May 2, 2003, which claims priority from U.S. Provisional Patent Application Serial No. 60/377,918, filed May 2, 2002 and is a continuation of U.S. Patent Application Serial No. 10/164,081, filed June 4, 2002, now U.S. Patent No. 6,624,626, which is a continuation-in-part of U.S. Patent Application Serial No. 09/430,978, filed November 1, 1999, now U.S. Patent No. 6,400,139. The entire content of each application is incorporated herein by reference.

FIELD OF THE INVENTION

This invention relates generally to position/orientation tracking and, in particular, to methods and apparatus for accurately tracking position, orientation and movement within a volume in the presence of electromagnetic distortion and/or noise.

BACKGROUND OF THE INVENTION

Position and orientation tracking systems ("trackers") are well known in the art. For example, U.S. Patents 4,287,809 and 4,394,831 to Egli et al.; U.S. Patent 4,737,794 to Jones; U.S. Patent 4,314,251 to Raab; and U.S. Patent 5,453,686 to Anderson, are directed to AC electromagnetic trackers. US Patent 5,645,077 to Foxlin discloses an inertial system, and combination systems, consisting or two different trackers, such as optical and magnetic, are described in U.S. Patent 5,831,260 to Hansen and U.S. Patent 6,288,785 B1 to Frantz et al. Other pertinent references include U.S. Patent 5,752,513 to Acker et al. and U.S. Patent 5,640,170 to Anderson.

AC electromagnetic trackers have definite advantages over other types of systems. For one, AC trackers provide the highest solution/update rate with the greatest

accuracy, not affected by obstructed field of view, in contrast to optical solutions. AC trackers do not require reference sensor/unit and drift stable apparatus of the type required by inertial units, and they are not affected by the Earth's magnetic field and ferrous materials, in contrast to DC magnetic systems.

The main disadvantage of AC trackers is that they are quite susceptible to distortion due to eddy currents in conductive materials in or near the motion box. To overcome this phenomenon, magnetic trackers often require costly and time-consuming calibration/mapping procedures to function correctly in the distorted environment. With mapping, the magnetic field profile is measured at multiple points associated with the volume of interest (motion box) prior to the actual tracking, as discussed in commonly assigned U.S. Patent No. 6,377,041 to Jones et al., and some of the references cited therein. While mapping may be done quickly and accurately, any changes in the motion box will require repeating of the mapping procedure.

Another approach, described in U.S. Patent 6,147,480 to Osadchy et al., allows the AC tracker to trace moving metal (distortion) by measuring the signal without distortion (acquiring baseline signals). This signal is then compared with a signal in the presence of distorting object(s) by measuring the phase error of the received signal. While such a system does work, it is not always practical to acquire baseline signal without distortion; in many cases, in an aircraft cockpit, for example, the distortion is always present.

The approach described in U.S. Patent 6,172,499 B1 to Westley introduces at least two frequencies per source channel, and uses the difference in responses to compensate for the eddy current distortion. This approach requires a guess about the eddy currents loop geometry, and the efficiency of the distortion compensation and operational frequencies depends on assumptions regarding the distorted environment, including the physical characteristics of the distorting materials where the system will be working. In addition, this approach requires a comparatively wide-band receiver (sensor and ADC processing), thus reducing noise stability.

The methods and apparatus for distortion compensated AC tracking described in our commonly assigned Patent Nos. 6,400,139 and 6,369,564, both to Khalfin et al., take advantage of wired "witness" sensors to obtain real-time information concerning the distortion (this is done by analyzing field profile that is superposition of the source field and distortion fields at the locations of "witness" sensors given sufficient "witness" sensors data). In addition, the '564 patent describes the signal processing from a resonantly tuned wireless passive sensor, 90° phase shifted with respect to the source to enable separation of the distortion signal.

Despite these advances, the need remains for apparatus and methods of compensation for spurious, eddy-current-induced fields in AC electromagnetic tracking systems. Such a solution could take advantage of the fact that the electromagnetic coupling which creates these eddy currents is strongly dependent on the frequency of the transmitted AC magnetic field. In addition, eddy currents are phase shifted with respect to the magnetic tracker source drive current that generates the magnetic field.

SUMMARY OF THE INVENTION

According to the system and method described herein, a bounding box or volume of interest is flooded with a modulated AC electromagnetic signal from a source. Different types of modulated signals may be used, including single-tone AM and FM. One or more sensors disposed on an object or body within the volume are then used to detect the signal, and a digital and/or analog spectral and phase analysis is performed on the received signal in hardware or software. The processing distinguishes between the direct source to sensor response and the response due to eddy currents. After removing the response due to the distorters, the electromagnetic position/orientation problem can be treated through a conventional "free-space" solution.

The disclosed system and methods do not require witness sensors, though the approach may be used in a combination with them. The invention operates in a narrow frequency band to ensure noise stability, and preferably uses high operating frequencies

(e.g., of about 20kHz - 50kHz) to ensure high signal quality and increased operation range.

A rapid solution update rate may be used to achieve real time (per frame) distortion compensation without any prior knowledge about physical properties of the distorters. At the same time, the system preserves all known advantages of AC trackers, but without the need for a calibration/mapping procedure, which has proven to be the main obstacle to more widespread applications of AC electromagnetic tracking technology.

The invention finds applicability in a wide variety of environments, including head tracking systems and helmet-mounted displays for fighter aircraft; head trackers for armored vehicles; medical-guided surgery and biopsy; remote sensing, among other potential uses.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a block diagram of a preferred embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

According to the invention, a source processor generates a modulated waveform, for example, a single-tone FM or single-tone AM signal, preferably having a modulation frequency close to the carrier frequency (for example, 30kHz carrier and 20kHz modulation). In the preferred embodiment, the waveform is detected by a sensor containing several non-coplanar coils, and a demodulation and spectral analysis is performed on the received signal.

The symmetry pattern of the carrier/satellites allows the system to distinguish between source-sensor coupling and source-distorter-sensor coupling, since each coupling modality is frequency-dependent and has unique phase characteristics. The restored source-sensor response then is plugged into a "free-space" solution which is well known in the art.

Thus, in contrast to prior-art systems, the inventive approach monitors and stabilizes the phase and the magnitude of the source (transmitter) current with respect to the internal reference. Without such stabilization, source drive current may change due to the electromagnetic coupling between the source and conducting materials in the volume of interest, as well as because of drift in electronics hardware.

A functional diagram of a system according to the preferred embodiment of the invention is presented in Figure 1. A source processor 111 generates the signal components representative of the modulated waveform. The modulated signal feeds source drivers 112 and is transmitted by a B-field source 113.

The modulated signal is received by a sensor or sensors 121, and the induction-vector components are demodulated and analyzed by analog and/or digital signal processors 122 and 123. At this stage, the signal is cleansed from the effects of the electromagnetic distortion. The resulting data is then transmitted to the "free-space" position and orientation processor 131, and the result is output to a utilization device via I/O controller 132.

It should be noted that the system with additional sensors working as "witnesses" might be arranged thus providing additional distortion and error correction. The use of witness sensors is disclosed in U.S. Patent No. 6,400,139 to Khalfin et al., the entire content of which is incorporated herein by reference.

The number of coils per sensor and per source may vary, depending on the number of DOF (degrees of freedom) to be measured. It is preferred to have three non-parallel sensor coils and three non-parallel source coils for six degrees of freedom. In addition to search coils, the sensors may use any appropriate magnetic flux sensing device including, but not limited to, solid-state (GMR or PSS), quantum (SQID), or flux gage sensors.

EXAMPLE

The method of distortion compensation in the case of single-tone FM modulation will now be described with the understanding that various alternative modulation schemes may be used.

The waveform generated by the source drive may be given as:

$$\cos(2\pi f_c t - \alpha \sin(2\pi f_m t)) \qquad (1)$$

This signal has well-pronounced components at f_c-f_m, f_c, and f_c+f_m, $f_c > f_m$.

The sensor(s) receive a signal that is time derivative of the source signal multiplied by a coupling constant that contains all sufficient information about position and orientation of the sensor with respect to the source. In a non-distorted environment, the data is sampled at 90 degrees behind the source, i.e., - *sin*DFT (discrete Fourier transform) and, after the DFT, the satellite and carrier components are:

$$\frac{\alpha}{2} b = S1 \qquad (2a)$$

$$b = S2 \qquad (2b)$$

$$-\frac{\alpha}{2} b = S3, \qquad (2c)$$

where $S1$, $S2$, and $S3$ are sensor responses normalized to the frequencies, b corresponds to the matrix element of the coupling matrix: $\|b\| = \mu\mu_o$ **Att** A_{eff} **D M**. All further considerations have as their goal the restoration of $S2$ in a distorted/scattering environment.

In the presence of distortion, an additional term quadratic with respect to the frequency (linear, after normalization) appears with magnitude a and with the phase shift of the carrier frequency φ, given that in this case the data are sampled at the zero phase of the non-distorted response. In general, the satellites exhibit different phase shifts from the carrier which are proportional to the deviation of frequencies. Note, no information or estimates about the values of φ and a are necessary for further computations.

For the ***Im*** part of the acquired signal, *e.g.*, 90 degrees behind the non-distorted source phase, we have:

$$-\frac{\alpha}{2} a 2\pi (f_c - f_m) \sin(\varphi - \Delta\varphi) + \frac{\alpha}{2} b = SD1 \qquad (3a)$$

$$-a 2\pi (f_c) \sin(\varphi) + b = SD2 \qquad (3b)$$

$$\frac{\alpha}{2} a\, 2\pi (f_c + f_m)\, \sin(\varphi + \Delta\varphi) - \frac{\alpha}{2} b = SD3 \qquad (3c)$$

For the ***Re*** part we have:

$$-\frac{\alpha}{2} a\, 2\pi (f_c - f_m)\, \cos(\varphi - \Delta\varphi) = CD1 \qquad (4a)$$

$$-a\, 2\pi (f_c)\, \cos(\varphi) = CD2 \qquad (4b)$$

$$\frac{\alpha}{2} a\, 2\pi (f_c + f_m)\, \cos(\varphi + \Delta\varphi) = CD3 \qquad (4c)$$

Combining terms in equations (3) and (4), and using symmetry of the satellites with respect to the carrier, we arrive at:

$$(SD1 + SD3)^2 + (CD1 - CD3)^2 - \alpha^2\, CD2^2 = \alpha^2\, (SD2 - S2)^2 \frac{f_m^2}{f_c^2} \qquad (5)$$

Taking into account practical consideration that the distortion contribution to the signal is not greater than the direct response and removing the ambiguity of sign we obtain the result:

$$S2 = b = sign(SD2)\left[-\frac{1}{\alpha} \frac{f_c}{f_m} \sqrt{(SD1 + SD3)^2 + (CD1 - CD3)^2 - \alpha^2\, CD2^2} + sign(SD2)\, SD2 \right] \qquad (6)$$

Equation (6) defines a restored, "non-distorted" signal in the presence of distortion.

The values of *b* from different sensor coils (3 for 6DOF) are sufficient to find position and attitude matrix as it was noted after equation (2).

I claim: